THIS MONTH'S LEADING FEATURE

Venturing Underground with VLF Radio

VLF Induction Radio Investigated by Mike Bedford, G4AEE*

THE RSGB HAS BEEN discussing the possibility of an LF/VLF allocation with the RA for some years. In the last year, encouraging responses have been obtained from the RA and there is now a very real possibility of obtaining a narrow experimental LF Amateur allocation.

As well as long distance communications, VLF is uniquely appropriate to communications underground and through rock, something which is of potential interest to miners and potholers alike, particularly in rescue situations. There is a considerable area of common interest between amateur LF/VLF operation and those experimenting with underground communications, and it seems appropriate to have an introductory article on this subject from them. This article is intended as an introduction to the topic of underground radio, and to encourage anyone who is interested in LF/VLF to consider this as a suitable avenue for their experimentation.

J Gannaway, G3YGF, Vice Chairman, Licensing Advisory Committee

IT IS 2.00 AM, AND A PARTY of six laden cavers grunt their way through the dark recesses of Dowber Gill passage beneath the flanks of Great Whernside in the Yorkshire Dales. For those who know it well, the trip between Providence Pot and Dow Cave, through the connecting mile long Dowber Gill Passage, is a pleasant and unthreatening experience. For inexperienced cavers, it can turn into a spiralling nightmare of route finding, exhaustion, and light failure, which inevitably results in members of the local rescue association being called out.

The missing party are found half way through the system - two hours journey from either end. Despite having been sitting in the cold, damp, and draughty conditions for over eight hours, most of the party are in reasonably good condition, and are rapidly revived by the hot soup and chocolate bought in by the rescue team. But one of the party, who is somewhat overweight, is very tired and gives some cause for concern.

It is rapidly agreed to take the casualties out of the Dow Cave entrance, and that an ambulance should be placed on standby near the entrance. The 87KHz Molefone [1] is taken out of its protective ammunition box, the antenna spread out over the floor of the cave, and two wake-up bleeps sent to the surface support person, standing on the moor 300 feet above their heads. He rapidly responds, and the underground party give full details of the situation, and their requirements. Surface support relays the information by radio to the surface controller, who passes it back to Base, who in turn pass the requirements through to the police.

By the time the underground party are out, everything is ready for them at the cave entrance. A surface party is ready to take the casualties; an ambulance and doctor are there to look at the patient; and most importantly, the dry clothes of the underground rescue team have been brought round the five miles by road from the Providence Pot entrance.

The above description of a typical cave rescue was provided by John Gardner of the Upper Wharfedale Fell Rescue Association, and illustrates the importance of radio communication links. The use of radio in emergency and rescue situations is a familiar concept to radio amateurs. What is somewhat out of the ordinary, however, is the use of the Molefone to transmit through 300 feet of solid rock.

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RADIO THROUGH ROCK

I GUESS THAT MOST people would be inclined to state that radio waves are quite effectively absorbed by rock, pre-stressed concrete, and most other solid conducting materials. On the evidence of car radios fading out under motorway bridges, it seems reasonable to assume that the attenuation is in the order of a few decibels per metre. For the frequency bands currently used by British radio amateurs, this would be a correct assumption. However, it is not a universal property of all radio waves. Let me introduce a bit of technical jargon which is frequently used in the realm of underground radio. The *skin depth* is a measure of how far a radio signal will pass into a conductive medium. To be more precise, it is the distance, in metres, at which the field strength is attenuated by 8.7dB (ie 63%).

The following formula shows how the skin depth, δ, varies with frequency, f, and the properties of the medium, specifically its magnetic permeability, μ, and its conductivity, σ:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

For most rocks, the magnetic permeability is reasonably constant. We are therefore left with the frequency and the conductivity as the major influences on a radio signal's passage through rock. In qualitative terms, it is clear that attenuation increases with both the frequency of the signal and the conductivity of the rock. We would therefore expect that the more conductive the medium, the lower the frequency which would be required to achieve effective communication. Let's look at some actual values. **Fig 1** shows a family of curves for various conductivities, each showing the variation of skin depth against frequency. The curves for 10^{-1}, 10^{-2} and 10^{-3} S/m correspond to low, average and high rock conductivities, 10^{-3} being reasonably typical of dry limestone, the rock in which caves and potholes are formed. Note, however, that with a significant cover of conductive material (eg soil), or the pres-

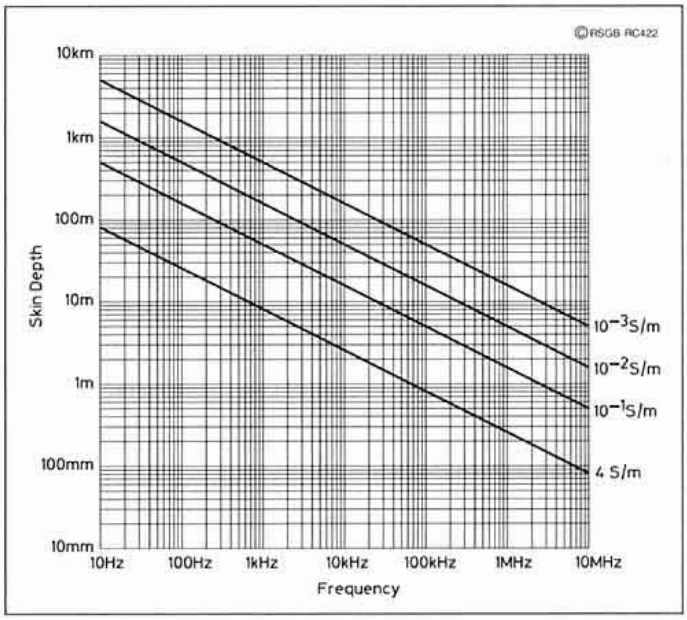

Fig 1: Skin depth vs frequency for various conductivities (in Siemens per metre).

The underground end of the cave-to-surface radio link on 87KHz.

ence of metal bearing minerals, this figure could be much higher. 4S/m is the conductivity of sea water. Although this is somewhat removed from our topic of underground radio, it has been provided to illustrate the similar, but more severe problems associated with submarine communication. It is not easy to translate skin depth into maximum range since radio signals also suffer attenuation in free space. Furthermore, as we shall see shortly, for the types of signals generated by cave radios, the signal drops off very rapidly with distance in free space, so this other term in the equation is quite significant. Nevertheless, it is clear that after quite a modest number of skin depths, very little of the transmitted signal will remain. In practice, most cave radios operate somewhere in the frequency range 800Hz to 200kHz. The US Navy's *Project Sanguine*, for submarine communication, operates on 75Hz.

FAR & NEAR FIELD

THOSE OF YOU WHO - due to space limitations - have struggled to erect an efficient Top Band antenna will immediately recognise the problems associated with communication at even 200kHz, let alone the figure of 800Hz mentioned earlier. Converting these figures to wavelengths, we get a range of 1500m to 375 km - a half wave dipole at 800Hz would reach from London to Birmingham!

It should also be borne in mind that impractical as VLF antennas may be on the surface, in a cramped cave passage, we're talking of something which is totally impossible. Certainly it's possible to make do with antennas shorter than a half-wave, but at the sort of fractional wavelengths we'd be talking about here, any antenna would be grossly inefficient, and very little power would actually be radiated.

Something which probably goes unnoticed to most radio amateurs, operating as they do comparatively high frequencies, is that if we look at fields much closer than half a wavelength from the aerial, the behaviour is very different from that which we find at greater distances. **Fig 2** shows the magnetic field pattern produced by a magnetic dipole in free space at various distances from this antenna. A magnetic dipole is approximated to by a small (compared to the wavelength) loop so long as we observe at a distance significantly greater than the loop diameter. In this diagram, the axis of the loop is pointing out of the paper. Exactly why I have chosen this antenna rather than the sort of thing encountered in ordinary radio will become clear shortly. In passing, I should make it clear that this diagram shows field patterns; it is not to be confused with an antenna gain polar diagram with which we are all familiar. At a few wavelengths from the antenna we see a circular pattern of field lines which are detached from the loop. As we get closer to the antenna, however, the pattern gradually changes until we eventually get the sort of field pattern normally associated with bar magnets. We are now in the vicinity of what is referred to as the *near field*, which has quite different properties from the *far field* which is normally considered as radio. The far field is true electromagnetic radiation, which means that a magnetic and an electric field co-exist in a fixed ratio. In the near field there is also a magnetic field and an electric field, but the ratio between them varies with distance, and different types of antenna favour the propagation of one type of field over the other. The near electric field is called the *electrostatic field* and the near magnetic field is normally referred to as the *induction field*. The good news about the induction field is that it can be generated effectively using loop antennas with dimensions far shorter than a wavelength. This is the technique employed for cave radio.

Before we jump to the conclusion that the use of small loop antennas and magnetic induction is the universal panacea, I should just point out one important feature of the induction field. With ordinary radio, both the electric and magnetic components of the field are attenuated in free space at a rate proportional to the distance travelled. In terms of power, therefore, we have an inverse square relationship. As alluded to earlier, however, the near magnetic field decays much more rapidly. It actually decays with the cube of distance, and there is a sixth power relationship between the distance and the power required to generate the field. So, for example, if a 10W transmitter achieves a range of 1000m, to increase the range to 2000m the power would need to rise to 640W. To get communication over a 20 mile path would require the output of five large power stations. Clearly this places a severe distance limitation on the range of magnetic induction, and for global communication, magnetic induction just isn't a viable proposition. However, if we remember that the purpose of cave radio is simply to communicate from a cave passage to the closest point on the surface, and since the deepest cave in the world is in the region of 1000m (and in the UK, 200m is about the limit), we can see that inductive communication is eminently suitable.

Above: Stuart France doing a radiolocation with his 874Hz rig. He is finding 'ground zero' by using triangulation.

Right: An angle of measurement is being taken by Stuart in order to determine depth.

HARDWARE REQUIREMENTS

Having now covered the theory of magnetic induction, albeit in somewhat simplistic terms, we can now turn our attention to the hardware

required. A good analogy of an induction radio system is a transformer with a very wide separation between its primary and secondary windings.

The field strength, H, on the loop axis and at a given distance, d, from the transmitter loop (ie the primary of the 'transformer') is given by:

$$H = \frac{M}{2\pi d^3}$$

where M, the *magnetic moment*, is given by:

$$M = I N A$$

where I is the current flowing in the loop, N is the number of turns in the loop, and A is the loop's cross-sectional area. The loops are normally tuned in order to present a purely resistive load and thereby maximise the current. A number of interesting conclusions follow from this formula. Although it would seem to suggest a large number of turns is beneficial, this is only true if all other factors remain constant. So, for example, if the number of turns is doubled, but the same gauge wire is used, the resistance doubles, the current halves, and so the magnetic moment remains the same. To achieve the intended gain, the cross sectional area of the wire would also have to be doubled. In other words, to get the two-fold increase in the magnetic field strength, a four-fold increase in weight is required. Since, as we've already seen, doubling the range involves producing an eight-fold increase in the field strength, to double the distance by adding more turns involves a 64-fold weight increase. In fact, it can be shown that the number of turns has no effect on the distance covered for a given power consumption.

All that really matters is the mass of copper in the wire, and for a given loop diameter, a lot of turns of thin wire and a few turns of thick wire give the same result. There are other reasons why a given number of turns may be favoured, but the strength of the resultant magnetic field is not one of them. If number of turns is not particularly significant, the same cannot be said of loop area. To maximise the magnetic moment, having decided on the maximum mass of copper you can tolerate, the loop should be made as large as possible. Clearly the size constraint of a typical cave passage doesn't lend itself to large diameter loops, so in the interests of portability, a 1m diameter is typical. Much larger loops have been used for the surface station, however.

Turning to the receiver loop (ie the secondary in our transformer analogy), the formula for the voltage induced, V, is:

$$V = 2\,\pi\,f\,N\,A\cos(\theta)\,\mu\,H$$

where f is the frequency, A is the loop's cross sectional area, N is the number of turns, θ is the angle of the loop to the lines of flux, μ is the magnetic permeability, and H is the magnetic field strength. This formula may suggest that, in contrast to the transmitting loop, the number of turns is significant. However more detailed analysis, taking into account the signal to noise ratio, atmospheric noise, and the thermal noise of the loop, indicates that once again, efficiency does not depend on the number of turns. One interesting aspect of this formula is the presence of frequency - the higher the frequency, the greater the induced voltage. This is at odds with the skin depth consideration which indicates that the higher the frequency the smaller the skin depth and hence the greater the attenuation. The implication is that for a given depth and rock conductivity there is an optimum frequency.

Space limitations preclude a discussion of the transmitter and receiver hardware. Suffice to say that although modulation and

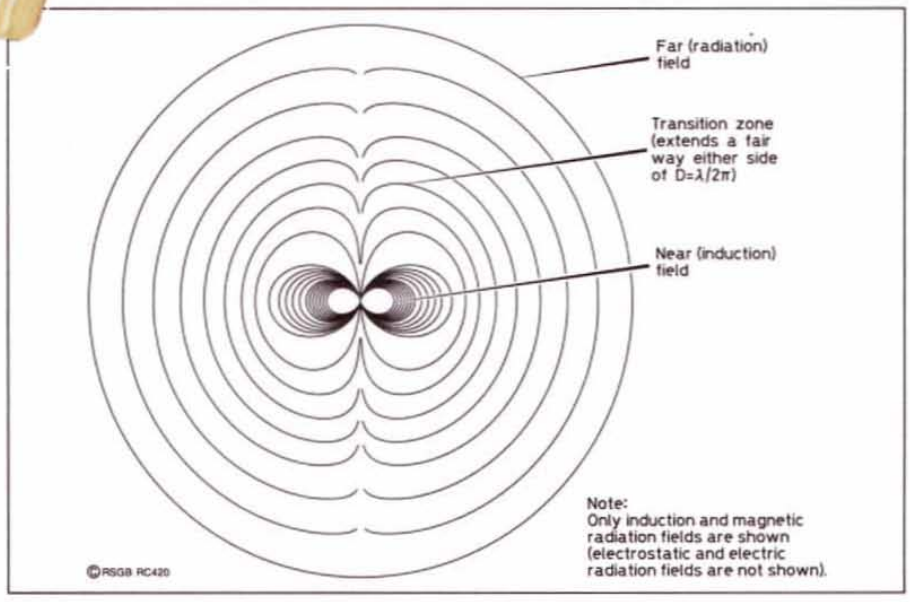
Far (radiation) field
Transition zone (extends a fair way either side of D=λ/2π)
Near (induction) field
Note:
Only induction and magnetic radiation fields are shown (electrostatic and electric radiation fields are not shown).
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Fig 2: Magnetic field pattern of a magnetic dipole.

demodulation techniques are similar to those employed in conventional amateur radio equipment, aspects such as the transmitter PA have more in common with audio than with RF design techniques.

RADIO LOCATION

THE WORLD OF THE POTHOLER doesn't normally hit the big time, yet on Saturday 28th May 1983, two cave divers, Geoff Yeadon and Geoff Crossley, emerged from Ingleborough Cave in North Yorkshire to a barrage of cameras, reporters and TV crews. The cause of the excitement was that eleven hours earlier they had abseiled down the 360ft shaft of Gaping Gill, one mile distant, and had become the first people to make this through trip - receiving the ultimate accolade in British caving. Although their skill, stamina and perseverance cannot be underestimated, the contribution of technology to this achievement must not be forgotten either. Had it not been for the vast improvements made to the surveys of both caves using radio location, the search for the elusive link could have taken years. To put this in amateur radio terms, radio location is DF in three dimensions, and is another application of inductive radio communications. Using this technique, an underground transmitter can be located on the surface to within a few metres, to provide fixed survey points within caves.

Since radio location in caves operates on the near magnetic field, the principles are somewhat different from those which appertain to normal radio direction finding. **Fig 3** shows how the magnetic lines of flux emanate from a horizontal loop in a cave. You will notice in (Fig 3(b)), that immediately above the transmitter, the lines of force have infinite curvature - ie they are straight vertical lines. Since small magnetic loops are highly directional, producing a sharp null, we have a suitable means of finding *ground zero*. The following is the procedure normally used.

One party of cavers is sent underground with a transceiver and loop, and an arrangement to contact a similarly equipped surface party is made. On reaching the point of interest, voice contact is made to ensure that the surface party is ready, and the underground transmitter loop is then accurately set up in the horizontal plane. A continuous carrier, or more usually - in the interests of power conservancy and ease of signal recognition - an on/off modulated carrier is then transmitted. The surface party now holds the receiving loop vertically, and rotates it around the vertical axis for a null. It is clear from Fig 3a, that once a null is detected, the plane of the loop will point towards ground zero. If this procedure is then carried out from one or more other positions, ground zero can be determined by triangulation. Frequently a more accurate result is obtained by taking further readings close to the calculated position. Having found ground zero, so long as the loop remains in the vertical plane, it can be rotated through any horizontal angle and no signal will be detected. This obviously provides a check on the position.

Having located the position in two dimensions, we now need to consider the depth of the transmitter. At any position other than ground zero, even with the face of the antenna pointing towards ground zero, a null can be achieved by rotating the loop from the vertical. This is clear from Fig 3b. The angle at which a null is obtained depends on both the distance from this point horizontally, and the depth of the transmitter. This, therefore, gives a means of determining the depth. However, since the lines of force are not straight lines, simple triangulation cannot be used. It wouldn't be appropriate to derive the equation here, suffice to say, that depth, d, is given by the following formula:

$$d = \frac{2x}{\sqrt{9\tan^2(\theta)+8} - 3\tan(\theta)}$$

where θ is the angle to the horizontal, and x is the distance from ground zero.

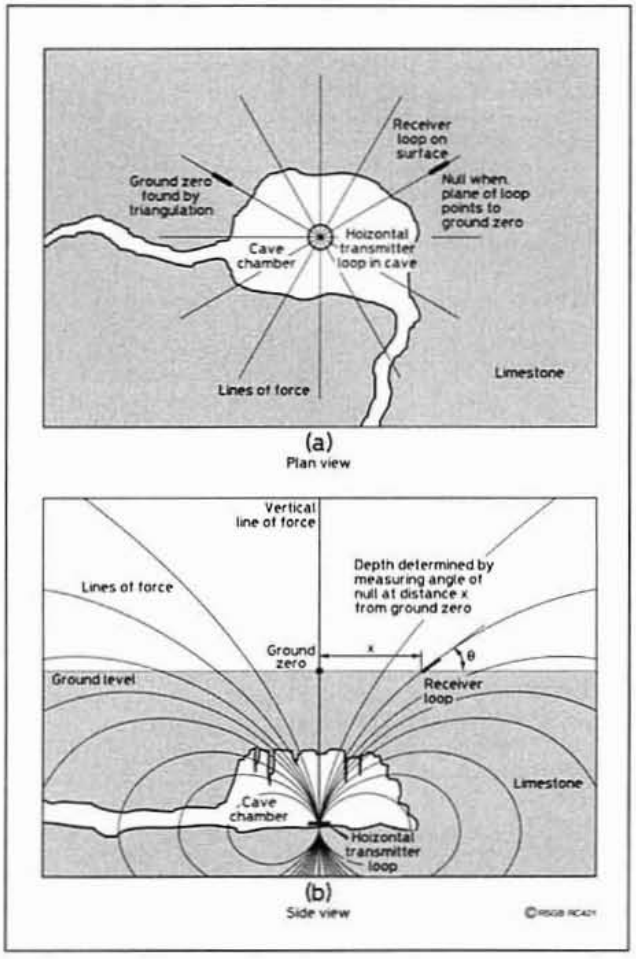

Fig 3: Plan view (a) and side elevation (b) of cave and magnetic lines of force.

A TYPICAL CIRCUIT

FOR THOSE WHO HAVE BEEN inspired to get their hands dirty (literally) with cave VLF or cave radio, I am presenting a circuit which was developed by Stuart France and Bob Mackin (the designer of the Molefone), and is reproduced with their permission. This design is for an 874Hz transmitter and receiver which could be used for radio location at depths to about 120m. With minor modifica-

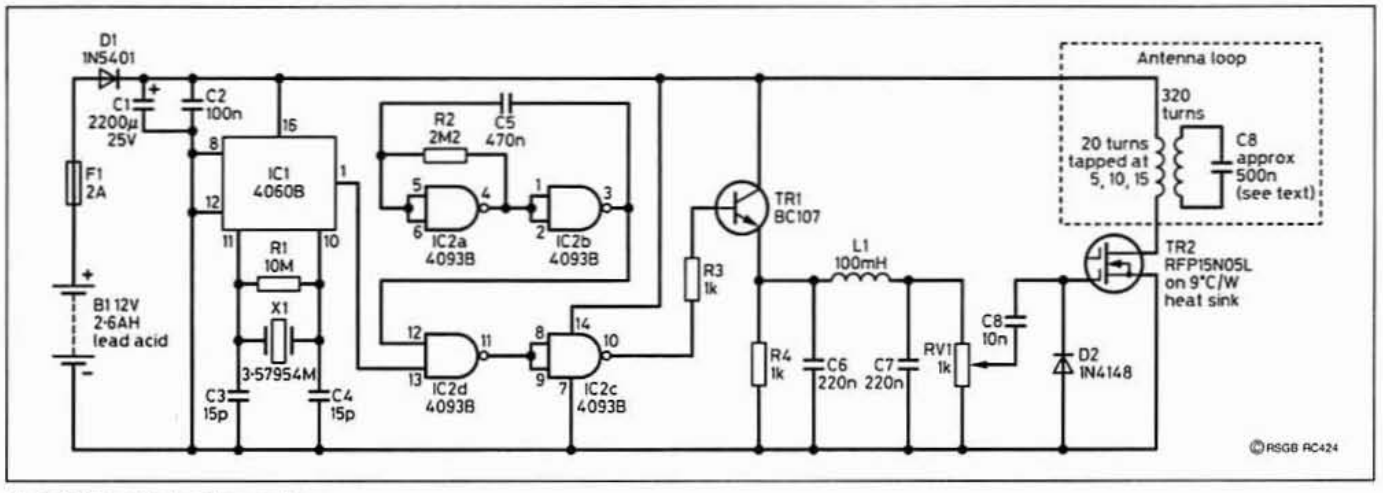

Fig 5: 874Hz radio-location receiver.

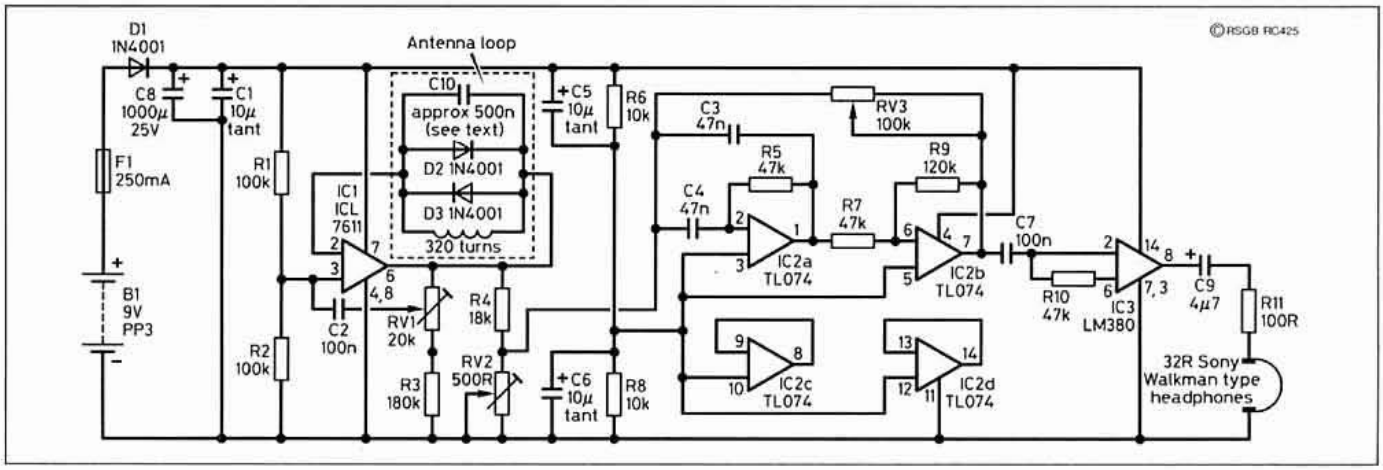

Fig 6: 874Hz radio-location transmitter.

tions it could also be used for CW or data transmission by on/off keying. It gives an idea of the techniques that might be used in equipment for an amateur VLF/LF allocation. First a few brief notes about the circuit.

The transmitter (**Fig 4**) consists of a 3.57954MHz crystal oscillator divided down by the 4060 to give the 874Hz signal frequency. A 1Hz square wave, generated by the 4093, is used to key the signal in a 50% duty cycle. The resultant signal is filtered to produce a pure sine wave which is amplified to drive the loop using a MOSFET. The transmitter antenna is tuned to resonance, and is linked to the PA via a primary link winding. The power output is set by RV1.

The receiver circuit (**Fig 5**) consists of three stages, a Q-multiplier, a bandpass filter and an audio amplifier. These are based around the 7611 CMOS opamp, TL074 FET quad-opamp, and LM380 integrated audio amplifier respectively. The receiver antenna is a multi-turn loop, tuned to resonance and with diode protection for strong signal conditions. RV1 is the Q multiplier control, and should be adjusted until ringing occurs, and then wound back slightly until stability returns. RV2 sets the filter's centre frequency, and should be adjusted for maximum signal at pin 3 of the TL074. RV3 sets the Q factor of the filter, and should be set in the same way as RV1.

With the exception of ensuring that all the components in the receiver's bandpass filter are as close to the IC as possible, the construction of the transmitter and the receiver is not critical. However, the winding of the antennas does require further explanation.

Both antennas are wound on a square former with 450mm sides. The former is constructed from four lengths of plastic conduit (the square type intended for surface mounting) with the top cover removed. The 'U' channel faces outwards and acts as a guide for the windings. During the winding process, a couple of struts are attached to one face in a cross. A hole is drilled in the middle of these struts and the whole assembly placed on a spindle to allow rotation whilst winding. A 500m drum of wire is placed on another spindle to allow free rotation. The wire is then wound from the drum onto the former in neat, ordered layers. For the transmitter loop, the link coil goes on first and consists of 20 turns of 16/0.2mm PVC-covered equipment wire tapped at 5, 10, and 15 turns. The main coil goes straight on top of this and consists of approximately 320 turns (ie a whole 500m reel) of 7/0.2mm PVC-covered equipment wire. The ends of the coils terminate in a small box attached to the inside of the former. This houses the tuning capacitors, diodes (for the receiver loop) and a socket. The receiver loop is identical to the transmitter loop with the exception of the link coil which is omitted, and the back-to-back diodes which are added.

The 500nF loop tuning capacitors should be built up from smaller (1000V, polypropylene type) capacitors in a series/parallel arrangement and adjusted for resonance by trial and error. Variable capacitors are impractical at these values.

PRACTICALITIES

WHEN TAKING ANY ELECTRONIC equipment underground, it is essential to make sure that everything is well waterproofed, as caves are wet places, and your comfort and safety could depend on the waterproofing. Waterproof ammo boxes are rugged, and can be used to protect electronics such as the transmitter, receiver or batteries, but the loop antennas would be more exposed to the elements. Potting the boxes and well varnishing the windings is strongly recommended.

LICENSING

THE CIRCUITS PRESENTED should give those interested in cave radio or VLF a feel for the issues which relate to VLF, underground radio and 'Cave Proofing' without going to the complexity of a full SSB design. Until an amateur VLF allocation is obtained, equipment such as that described here can only really be used under a Technical and Development Licence. However, these licences are expensive, and the usage must be strictly test and development - it precludes the operational use of the equipment, but it might be used to develop equipment to meet MPT1337.

The RA specification MPT1337 covers type approved equipment for inductive communications, and equipment which complies with this specification does not need a licence, as it is licence exempt. This is obviously the ideal solution for non technically minded cavers and rescue groups, but the cost of obtaining type approval for a new design is very significant to non-commercial organisations, being measured in thousands of pounds.

There is a variety of type approved equipment available commercially for more conventional applications, and some of this could be used to gain experience with short range VLF propagation; however, it is part of the type approval requirements that this equipment must not be modified in any way, and so this allows relatively little scope for experimentation.

Underground communication is clearly an interesting area, and is the only way of proving that VLF signals can be transmitted through solid rock. It also offers some interesting challenges in making equipment waterproof and rugged. I hope this article has encouraged some of you to consider this aspect of VLF propagation if an allocation becomes available.

SAFETY WARNING

MANY PEOPLE also find that transmitting through rock for the first time is a great thrill. However, I must stress in the strongest possible terms, that if you're not an experienced caver, you should not wander into caves unescorted. I'm sure I don't have to labour the point, but caves and potholes are potentially very dangerous places. However, all the risks can be virtually eliminated by taking sensible precautions. First and foremost, you should seek out a caving club and make your first trips underground in the company of people who can guide you into good caving practice. To find out details of a caving club in your area, contact the National Caving Association at Monomark House, 27 Old Gloucester St., London WC1N 3XX.

CONTACT

YOU MIGHT ALSO LIKE to consider joining the Cave Radio & Electronics Group (CREG) of the British Cave Research Association (BCRA). The CREG publishes a quarterly *Journal* which includes a good deal of coverage on induction radio, arranges regular field meetings, and can - of course - put you in contact with like minded people in your area. For information, send a 9" x 4" SAE to the author.

REFERENCES

[1] 'VLF Link for Cave Station', *RadCom*, October '94, p7. ♦